

# GROUPS, WAVELETS, AND WAVELET SETS

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**ABSTRACT.** Wavelet and frames have become a widely used tool in mathematics, physics, and applied science during the last decade. This article gives an overview over some well known results about the continuous and discrete wavelet transforms and groups acting on  $\mathbb{R}^n$ . We also show how this action can give rise to wavelets, and in particular, MSF wavelets in  $L^2(\mathbb{R}^n)$ .

## INTRODUCTION

The classical wavelet system consists of a single function  $\psi \in L^2(\mathbb{R})$  such that  $\{2^{j/2}\psi(2^jx+k) \mid j, k \in \mathbb{Z}\}$  is an orthonormal basis for  $L^2(\mathbb{R})$ . There has been quite a bit of recent interest in relaxing various aspects of the definition of wavelets, in particular in higher dimensions. For example, one can allow multiple functions  $\psi^1, \dots, \psi^L$ , an arbitrary matrix of dilations, and an arbitrary lattice of translations. One could relax even further to allow a group of dilations, or perhaps even just a set of dilations and translations. A first question one would ask, then, is: for which collections of dilations and translations do there exist wavelets? We will begin by reviewing some well-known results concerning this central question. Then, we will show that there is a fundamental connection between the papers of Dai, Diao, Gu and Han [15], Fabec and Ólafsson [21], Laugesen, Weaver, Weiss and Wilson [45], and Wang [56]. One argument that a survey paper such as this one is useful is that, even though these eleven authors are active in the field, there is only one cross-reference of the above papers in the references of the other papers.

We now describe briefly the connection between the papers listed above. All four papers are concerned with constructing reproducing systems consisting of dilations and translations of a function. That is, they consider triples  $(\mathcal{D}, \mathcal{T}, M)$ , where  $\mathcal{D}$  is some collection of invertible matrices,  $\mathcal{T}$  is some collection of points in  $\mathbb{R}^n$ , and  $M$  a non-trivial closed subspace of  $L^2(\mathbb{R}^n)$ . Then, they ask whether there is a function  $\psi$  such that  $\{\psi_{a,k} = |\det a|^{1/2} \psi(a(x) + k) \mid a \in \mathcal{D}, k \in \mathcal{T}\}$  is a frame, normalized tight frame, or even a orthonormal basis for  $M$ .

In [15], it is assumed that  $\mathcal{D} = \{a^j \mid j \in \mathbb{Z}\}$  for some expansive matrix  $a$ , that  $\mathcal{T} = \mathbb{Z}^n$ , and that  $M$  is an  $a$ -invariant subspace of  $L^2(\mathbb{R}^n)$ . In [21], the assumptions are that,  $\mathcal{D}$  is constructed as a subset of a particular type of group  $H$ , that  $\mathcal{T}$  is a full rank lattice depending on  $H$ , and finally that  $M$  is of the form  $M = \{f \in L^2(\mathbb{R}^n) \mid \text{Supp}(\hat{f}) \subseteq \overline{\mathcal{O}}\}$ , where  $\mathcal{O} \subset \mathbb{R}^n$  is an open  $H$ -orbit. In [45], it is assumed that  $\mathcal{D}$  is a group,  $\mathcal{T} = \mathbb{Z}^n$ , and  $M = L^2(\mathbb{R}^n)$ . In [56], it is assumed that  $\mathcal{D}$  and  $\mathcal{T}$  satisfy non-algebraic conditions relating to the existence of fundamental regions (see Section 1 for details) and  $M = L^2(\mathbb{R}^n)$ . Moreover, all four papers - either explicitly or implicitly - are concerned primarily with the existence of functions of the form  $\hat{\psi} = \chi_{\Omega}$ .

When put in this general framework, it becomes clear that the four papers are related in spirit and scope. What we will show below is that they are also related in that results in [15] can be used to remove technical assumptions from results in [56]. The improved results in [56] can then be used to improve the results in [45] and [21]. We will improve the results in [21] by removing the dependence of the lattice on the group, and by constructing an orthonormal basis where a normalized tight frame was constructed

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before. The proof of the main Theorem in [21] will also be simplified. Finally, we improve the results in [45] by replacing normalized tight frame system with a wavelet system.

We will attempt to make these technical improvements to the theorems in these papers with a minimal amount of technical work. In particular, where possible, we will apply theorem quoting proofs. The primary exception to this is Theorem 1.17, where we essentially need to check that the details of an argument in [18] go through in a slightly more general setting.

## 1. WAVELET SETS

We start this section by recalling some simple definitions and facts about wavelets, wavelet sets, and tilings. For a measurable set  $\Omega \subseteq \mathbb{R}^n$  we denote by  $\chi_\Omega$  the indicator function of the set  $\Omega$  and by  $|\Omega| = \int \chi_\Omega(x) dx$  the measure of  $\Omega$ .

**Definition 1.1.** A countable collection  $\{\Omega_j\}$  of subsets of  $\mathbb{R}^n$  is a (measurable) tiling of  $\mathbb{R}^n$  if  $|\mathbb{R}^n \setminus \bigcup_j \Omega_j| = 0$ , and  $|\Omega_i \cap \Omega_j| = 0$  for  $i \neq j$ .

**Definition 1.2.** Let  $\mathcal{T} \subset \mathbb{R}^n$  and  $\mathcal{D} \subset \text{GL}(n, \mathbb{R})$ . We say that  $\mathcal{D}$  is a *multiplicative tiling set* of  $\mathbb{R}^n$  if there exists a set  $\Omega \subset \mathbb{R}^n$  of positive measure such that  $\{d(\Omega) \mid d \in \mathcal{D}\}$  is a tiling of  $\mathbb{R}^n$ . The set  $\Omega$  is said to be a *multiplicative  $\mathcal{D}$ -tile*. We say  $\mathcal{D}$  is a *bounded multiplicative tiling set* of  $\mathbb{R}^n$  if there is a multiplicative  $\mathcal{D}$ -tile  $\Omega$  which is bounded and such that  $0 \notin \overline{\Omega}$ .

Similarly, we say that  $\mathcal{T}$  is an *additive tiling set* of  $\mathbb{R}^n$  if there exists a set  $\Omega \subset \mathbb{R}^n$  such that  $\{\Omega + x \mid x \in \mathcal{T}\}$  is a tiling of  $\mathbb{R}^n$ . The set  $\Omega$  is said to be an *(additive)  $\mathcal{T}$  tile*. Again, we add the word bounded if  $\Omega$  can be chosen to be a bounded set (with no restriction on being bounded away from 0).

A set  $\Omega$  is a  $(\mathcal{D}, \mathcal{T})$  *tiling set* if it is a  $\mathcal{D}$  multiplicative tiling set and a  $\mathcal{T}$  additive tiling set.

Note that this definition does not coincide with the definition of Wang [56]. Wang defines a multiplicative tiling set to be what we have defined to be a bounded multiplicative tiling set. We feel that boundedness properties of  $\mathcal{D}$ -tiles are interesting properties, but they should not be part of a definition of tiling.

Multiplicative and additive tilings of  $\mathbb{R}^n$  show up in wavelet theory and other branches of analysis in a natural way.

**Definition 1.3.** A function  $\varphi \in L^2(\mathbb{R}^n)$  is called a *wavelet* if there exists a subset  $\mathcal{D} \subset \text{GL}(n, \mathbb{R})$  and a subset  $\mathcal{T} \subset \mathbb{R}^n$  such that

$$\mathcal{W}(\varphi; \mathcal{D}, \mathcal{T}) := \{|\det d|^{1/2} \varphi(dx + k) \mid d \in \mathcal{D}, k \in \mathcal{T}\}$$

forms an orthonormal basis for  $L^2(\mathbb{R}^n)$ . The set  $\mathcal{D}$  is called the *dilation set* for  $\varphi$ , the set  $\mathcal{T}$  is called the *translation set* for  $\varphi$ , and we say that  $\varphi$  is a  $(\mathcal{D}, \mathcal{T})$ -wavelet.

Normalize the Fourier transform by

$$\mathcal{F}(f)(\lambda) = \hat{f}(\lambda) = \int_{\mathbb{R}^n} f(x) e^{2\pi i(\lambda, x)} dx.$$

We set  $f^\vee(x) = \hat{f}(-x)$ . Then  $f = (\hat{f})^\vee$ . For simplicity we set  $e_\lambda(x) = e^{2\pi i(\lambda, x)}$ .

**Definition 1.4.** Let  $\Omega \subset \mathbb{R}^n$  be measurable with positive, but finite measure. We say that  $\Omega$  is a *wavelet set* if there exists a pair  $(\mathcal{D}, \mathcal{T})$ , with  $\mathcal{D} \subset \text{GL}(n, \mathbb{R})$  and  $\mathcal{T} \subset \mathbb{R}^n$  such that  $\chi_\Omega^\vee$  is a  $(\mathcal{D}, \mathcal{T})$ -wavelet. If  $\chi_\Omega^\vee$  is a  $(\mathcal{D}, \mathcal{T})$ -wavelet, then we say that  $\Omega$  is a  $(\mathcal{D}, \mathcal{T})$ -wavelet set.

**Definition 1.5.** A measurable set  $\Omega \subset \mathbb{R}^n$  with finite positive measure is called a *spectral set* if there exists a set  $\mathcal{T} \subset \mathbb{R}^n$  such that the sequence of functions  $\{e_\lambda\}_{\lambda \in \mathcal{T}}$  forms an orthogonal basis for  $L^2(\Omega)$ . If this is the case we say that  $\mathcal{T}$  is the *spectrum* of  $\Omega$ , and say that  $(\Omega, \mathcal{T})$  is a spectral pair

Now, after given this list of definitions, let us recall some results, questions, and conjectures on how these concepts are tied together. A first result, which has appeared in several places [16, 35, 39] is

**Theorem 1.6.** *A measurable set  $\Omega \subset \mathbb{R}$  is a wavelet set for the pair  $\mathcal{D} = \{2^n \mid n \in \mathbb{Z}\}$  and  $\mathcal{T} = \mathbb{Z}$  if and only if  $\Omega$  is a  $(\mathcal{D}, \mathcal{T})$ -tiling set.*

For the general case we have now the following two related questions:

**Question 1** (Wang, [56]). For which sets  $\mathcal{D} \subset \text{GL}(n, \mathbb{R})$ ,  $\mathcal{T} \subset \mathbb{R}^n$  do there exist  $(\mathcal{D}, \mathcal{T})$ -wavelets?

**Question 2.** For which sets  $\mathcal{D} \subset \text{GL}(n, \mathbb{R})$ ,  $\mathcal{T} \subset \mathbb{R}^n$  do there exist  $(\mathcal{D}, \mathcal{T})$ -wavelet sets?

Clearly, if there exists a  $(\mathcal{D}, \mathcal{T})$  wavelet set, then there exists a  $(\mathcal{D}, \mathcal{T})$  wavelet, but, what is interesting, is that the converse may also be true. In particular, there are currently no examples known of sets  $(\mathcal{D}, \mathcal{T})$  for which there exist wavelets, but for which there do not exist  $(\mathcal{D}, \mathcal{T})$  wavelet sets. Therefore we can state the third natural question:

**Question 3.** Is it true that if there exists a  $(\mathcal{D}, \mathcal{T})$  wavelet, then there exists a  $(\mathcal{D}, \mathcal{T})$  wavelet set?

So far, all evidence points to a positive answer for question 3. (Though, we should point out that question 3 has mostly been thought about in the case that  $\mathcal{D}$  is a singly generated group and  $\mathcal{T}$  is a full rank lattice, so it is possible that there is a relatively easy counterexample to the question posed in this generality.) When  $\mathcal{D}$  is generated by a single matrix  $a$  and  $\mathcal{T}$  is a lattice, it is known [17] that if  $a$  is expansive, then there exist  $(\mathcal{D}, \mathcal{T})$  wavelet sets. Moreover, it is also known [11, 13, 14] in the expansive case that there exist  $(\mathcal{D}, \mathcal{T})$  wavelets that do not come from a wavelet set if and only if there is a  $j \neq 0$  such that  $(a^T)^j(\mathcal{T}^*) \cap \mathcal{T}^* \neq \{0\}$ . In particular, for *most* pairs of this type, the *only* wavelets that exist come from wavelet sets. When  $\mathcal{D}$  is generated by a not necessarily expansive matrix  $a$  and  $\mathcal{T}$  is a lattice, then the handful of  $(\mathcal{D}, \mathcal{T})$  wavelets known all come from  $(\mathcal{D}, \mathcal{T})$  wavelet sets.

There is also a stronger version of question 3 due to Larson [44] in the one dimensional case.

**Question 4** (Larson, [44]). Is it true that if  $\psi$  is a  $(\mathcal{D}, \mathcal{T})$  wavelet, then there is a  $(\mathcal{D}, \mathcal{T})$  wavelet set  $E \subseteq \text{supp}(\hat{\psi})$ ?

This problem is open even for the “classical” case of dimension 1 with dilations by powers of 2 and translations by integers. We name two partial answers. The first is given by Rzeszotnik in his PhD Thesis, and the second is due to Rzeszotnik and the second author of this paper.

**Theorem 1.7** (Rzeszotnik, [51] Corollary 3.10). *Every multiresolution analysis (MRA)  $(2^j, \mathbb{Z})$  wavelet contains in its support the support of its Fourier transform an MRA  $(\mathcal{D}, \mathcal{T})$  wavelet set.*

**Theorem 1.8.** [52] *If  $\psi$  is a classical wavelet and the set  $K = \text{supp}(\hat{\psi})$  satisfies*

- (1)  $\sum_{k \in \mathbb{Z}} \chi_K(\xi + k) \leq 2$  a.e.;
- (2)  $\sum_{k \in \mathbb{Z}} \chi_K(2^j \xi) \leq 2$  a.e.

*Then  $K$  contains a wavelet set.*

Qing Gu has an unpublished example which shows that the techniques in [52] do not extend to the case that  $\sum_{k \in \mathbb{Z}} \chi_K(\xi + k) \leq 3$  a.e. and  $\sum_{j \in \mathbb{Z}} \chi_K(2^j \xi) \leq 3$  a.e.

Tilings and spectral sets are related by the *Fuglede conjecture* [26]

**Conjecture 1** (Fuglede). *A measurable set  $\Omega$ , with positive and finite measure is a spectral set if and only if  $\Omega$  is an additive  $\mathcal{T}$  tile for some set  $\mathcal{T}$ .*

The conjecture, in general, still remains unsolved, even if several partial results have been obtained [40, 43, 41, 42, 56]. In June 2003 it was shown by Tao, [55] that the conjecture is false in dimension 5 and higher. We will not discuss those articles, but concentrate on the important paper [56] by Wang,

which also made the first serious attempt at studying  $(\mathcal{D}, \mathcal{T})$  wavelet sets when  $\mathcal{D}$  is not even a subgroup of  $\mathrm{GL}(n, \mathbb{R})$ , and  $\mathcal{T}$  is not a lattice. We need two more definitions before we state some of Wang's results. Let  $a \in \mathrm{GL}(n, \mathbb{R})$ . A set  $\mathcal{D} \subseteq \mathrm{GL}(n, \mathbb{R})$  is said to be *a* invariant if  $\mathcal{D}a = \mathcal{D}$ . The multiplicative tiling set  $\mathcal{D}$  said to satisfy the *interior condition* if there exists a multiplicative  $\mathcal{D}$ -tile  $\Omega$  such that  $\Omega^\circ \neq \emptyset$ . Similarly the spectrum  $\mathcal{T} \subset \mathbb{R}^n$  satisfies the *interior condition* if there exists a measurable set  $\Omega \subset \mathbb{R}^n$  such that  $\Omega^\circ \neq \emptyset$  and  $(\Omega, \mathcal{T})$  is a spectral pair. With these definitions we can state two of Wang's main results:

**Theorem 1.9** (Wang, [56]). *Let  $\mathcal{D} \subset \mathrm{GL}(n, \mathbb{R})$  and  $\mathcal{T} \subset \mathbb{R}^n$ . Let  $\Omega \subset \mathbb{R}^n$  be measurable, with positive and finite measure. If  $\{d^T(\Omega) \mid d \in \mathcal{D}\}$  is a tiling of  $\mathbb{R}^n$  and  $(\Omega, \mathcal{T})$  is a spectral pair, then  $\Omega$  is a  $(\mathcal{D}, \mathcal{T})$ -wavelet set. Conversely, if  $\Omega$  is a  $(\mathcal{D}, \mathcal{T})$ -wavelet set and  $0 \in \mathcal{T}$ , then  $\Omega$  is a multiplicative  $\mathcal{D}^T$ -tile and  $(\Omega, \mathcal{T})$  is a spectral pair.*

**Theorem 1.10** (Wang, [56]). *Let  $\mathcal{D} \subset \mathrm{GL}(n, \mathbb{R})$  such that  $\mathcal{D}^T := \{d^T \mid d \in \mathcal{D}\}$  is a bounded multiplicative tiling set, and let  $\mathcal{T} \subset \mathbb{R}^n$  be a spectrum, with both  $\mathcal{D}^T$  and  $\mathcal{T}$  satisfying the interior condition. Suppose that  $\mathcal{D}^T$  is *a*-invariant for some expanding matrix *a* and  $\mathcal{T} - \mathcal{T} \subset \mathcal{L}$  for some lattice  $\mathcal{L}$  of  $\mathbb{R}^n$ . Then, there exists a wavelet set  $\Omega$  with respect to  $\mathcal{D}$  and  $\mathcal{T}$ .*

In his paper, Wang states “The assumption that  $\mathcal{D}^T \dots$  have the interior condition is most likely unnecessary. All known examples of multiplicative tiling sets admit a tile having nonempty interior.” In this section, we will in fact show that the assumption that  $\mathcal{D}^T$  satisfies the interior condition is indeed unnecessary, but not by proving that every multiplicative tiling set admits a tile having nonempty interior. Instead, we will use a Lebesgue density argument as in [18, 15]. Moreover, the assumption of multiplicative tiling sets having prototiles that are bounded and bounded away from the origin is not a “wavelet” assumption, but rather it is motivated from the point of view of tiling questions and the relation between translation and dilation tilings of the line. From the point of view of wavelets, by Theorem 1.9, one does not always wish to restrict to bounded multiplicative tiling sets. There are, however, some benefits of obtaining wavelet sets that are bounded and bounded away from the origin - especially if they also satisfy some additional properties. For example, if the sets are the finite union of intervals, one can use these wavelets to show that theorems about the poor decay of wavelets in  $L^2(\mathbb{R}^n)$  for “bad” dilations are optimal. Along these lines, Bownik [12] showed that if *a* is irrational and  $\psi_1, \dots, \psi_L$  is an  $(A, \mathbb{Z})$  multiwavelet, then there is an *i* such that for each  $\delta > 0$ ,  $\limsup_{|x| \rightarrow \infty} |\psi_i| |x|^{1+\delta} = \infty$ . He also showed that this result is sharp by finding wavelet sets for each of these dilations that are the union of at most three intervals. Another possibility is to use wavelet sets that are the finite union of intervals (and satisfying several extra conditions) as a start point for the smoothing techniques in [16, 39]. However, these two advantages come from having wavelet sets that are not only bounded and bounded away from the origin, but also the finite union of intervals. In the construction considered in [56], it is not clear at all whether the end wavelet sets can be chosen to be the finite union of nice sets. In fact, the construction used of Benedetto and Leon was used originally exactly to construct fractal-like wavelet sets.

Since the general question of existence of wavelet sets is phrased not in terms of sets bounded and bounded away from the origin, but arbitrary measurable sets, we will also show that the assumption that there exist a multiplicative tiling set that is bounded and bounded away from the origin is unnecessary. This will be done by showing that whenever there is a set that tiles  $\mathbb{R}^n$  by  $\mathcal{D}$  dilations, where  $\mathcal{D}$  is invariant under an expansive matrix, then there exists a bounded multiplicative tiling set for  $\mathcal{D}$ .

We begin with some easy observations that were also in [56]. We say that sets  $U$  and  $V$  in  $\mathbb{R}^n$  are *a*-dilation equivalent if there is a partition  $\{U_k : k \in \mathbb{Z}\}$  of  $U$  such that  $\{a^k U_k \mid k \in \mathbb{Z}\}$  is a partition of  $V$ .

**Lemma 1.11.** *Let  $\mathcal{D} \subset \mathrm{GL}(n, \mathbb{R})$  invariant under the invertible matrix *a*. If  $\{d\Omega \mid d \in \mathcal{D}\}$  is a tiling of  $\mathbb{R}^n$  and  $\Omega_0$  is *a*-dilation equivalent to  $\Omega$ , then  $\{d\Omega_0 \mid d \in \mathcal{D}\}$  is a tiling of  $\mathbb{R}^n$ .*

*Proof.* Let  $S_k$  be a partition of  $\Omega$  such that  $\Omega_0 = \bigcup_{k \in \mathbb{Z}} a^k(S_k)$ . Then,

$$\begin{aligned} \bigcup_{d \in \mathcal{D}} d\Omega_0 &= \bigcup_{D \in \mathcal{D}} \bigcup_{j \in \mathbb{Z}} da^j S_j \\ &= \bigcup_{j \in \mathbb{Z}} \bigcup_{d \in \mathcal{D}} da^j S_j \\ &= \bigcup_{j \in \mathbb{Z}} \bigcup_{d \in \mathcal{D}} dS_j = \mathbb{R}^n. \end{aligned}$$

Similarly, one can show that  $d_1\Omega_0 \cap d_2\Omega_0$  has measure 0 for all  $d_1 \neq d_2$  in  $\mathcal{D}$ .  $\square$

**Lemma 1.12.** *Let  $A$  be an expansive matrix and  $\Omega_0, \Omega_1$  be such that  $|A^j\Omega_i \cap A^k\Omega_i| = \delta_{j,k}$  for  $i = 1, 2$ . Then,  $\Omega_0$  is  $A$  equivalent to  $\Omega_1$  if and only if  $\bigcup_{j \in \mathbb{Z}} A^j\Omega_0 = \bigcup_{j \in \mathbb{Z}} A^j\Omega_1$  a.e.*

**Proposition 1.13.** *Let  $\mathcal{D} \subset \text{GL}(n, \mathbb{R})$  be invariant under the expansive matrix  $a$ . If there is a set  $\Omega \subset \mathbb{R}^n$  such that  $\{d\Omega \mid d \in \mathcal{D}\}$  tiles  $\mathbb{R}^n$ , then there is a set  $\Omega_0$  bounded and bounded away from the origin such that  $\{d\Omega_0 \mid d \in \mathcal{D}\}$  tiles  $\mathbb{R}^n$ . In particular,  $\mathcal{D}$  is a bounded multiplicative tiling set.*

*Proof.* It is widely known that  $a$  is expansive if and only if there is an ellipsoid  $\mathcal{E}$  such that  $\overline{\mathcal{E}} \subset a\mathcal{E}^\circ$ . In this case, it is easy to check that  $\Omega_1 = a\mathcal{E} \setminus \mathcal{E}$  is a bounded multiplicative tiling set for  $\{a^j \mid j \in \mathbb{Z}\}$ ; that is,  $\Omega_1$  is bounded and bounded away from the origin, and  $\{a^j\Omega_1 \mid j \in \mathbb{Z}\}$  tiles  $\mathbb{R}^n$ . Let  $S_j = a^j(\Omega_1) \cap \Omega$ , and  $\Omega_0 = \bigcup_{j \in \mathbb{Z}} a^{-j}S_j$ . It is clear that  $\Omega_0 \subset \Omega_1$ , so it is bounded and bounded away from the origin. Moreover, since  $\{a^j(\Omega_1) \mid j \in \mathbb{Z}\}$  is a tiling of  $\mathbb{R}^n$ , it follows that  $\{S_j \mid j \in \mathbb{Z}\}$  is a partition of  $\Omega$ ; hence,  $\Omega_0$  is  $a$ -dilation equivalent to  $\Omega$ . Therefore, by lemma 1.13,  $\Omega_0$  is a multiplicative tiling set.  $\square$

Next, we turn to showing that the assumption of a multiplicative tile with non-empty interior is unnecessary. We have (combining Lemma 2 and Theorem 1 of 1.14):

**Theorem 1.14** ([15]). *Let  $M$  be a measurable subset of  $\mathbb{R}^n$  with positive measure satisfying  $aM = M$  for some expansive matrix  $a$ . Then, there exists a set  $E \subset M$  such that  $\{E + k \mid k \in \mathbb{Z}^n\}$  tiles  $\mathbb{R}^n$  and  $\{a^j E \mid j \in \mathbb{Z}\}$  tiles  $M$ .*

Suppose that we are considering classes of  $(\mathcal{D}, \mathcal{T})$  wavelets, where  $\mathcal{D} = \{a^j \mid j \in \mathbb{Z}\}$  and  $\mathcal{T}$  is a lattice. It is a general principle that one can either assume that  $a$  is in (real) Jordan form, in which case one must deal with arbitrary lattices, or one can assume that the lattice  $\mathcal{T} = \mathbb{Z}^n$ , in which case one needs to consider all matrices of the form  $bab^{-1}$ . In particular, if one is working with expansive matrices, it is almost always permissible to restrict attention to translations by  $\mathbb{Z}^n$ . While this is clear to experts in the field, it is likely that researchers new to this field are not aware that the above theorem is really a theorem about arbitrary lattices.

Indeed, let  $M$  be a measurable subset of  $\mathbb{R}^n$  with positive measure satisfying  $aM = M$ , for some expansive matrix  $a$ . Let  $\mathcal{L}$  be a full rank lattice in  $\mathbb{R}^n$ . Then, there is an invertible matrix  $b$  such that  $b\mathcal{L} = \mathbb{Z}^n$ . The set  $bM$  is  $bab^{-1}$  invariant, and  $bab^{-1}$  is an expansive matrix, so there is a set  $F$  such that  $\{F + k \mid k \in \mathbb{Z}^n\}$  tiles  $\mathbb{R}^n$  and  $\{ba^jb^{-1}F \mid j \in \mathbb{Z}\}$  tiles  $bM$ . We claim that for  $E = b^{-1}F$ ,  $\{E + k \mid k \in \mathcal{L}\}$  tiles  $\mathbb{R}^n$  and  $\{a^j E \mid j \in \mathbb{Z}\}$  tiles  $M$ . Indeed,

$$\begin{aligned} \bigcup_{k \in \mathcal{L}} E + k &= \bigcup_{k \in \mathcal{L}} b^{-1}F + k \\ &= \bigcup_{k \in \mathcal{L}} b^{-1}(F + bk) \\ &= \bigcup_{k \in \mathbb{Z}^n} b^{-1}(F + k) \end{aligned}$$

$$\begin{aligned}
&= b^{-1} \left( \bigcup_{k \in \mathbb{Z}^n} (F + k) \right) \\
&= \mathbb{R}^n.
\end{aligned}$$

One can similarly show the disjointness of translates by  $\mathcal{L}$ . To see that  $\{a^j E \mid j \in \mathbb{Z}\}$  tiles  $M$ , note that

$$\begin{aligned}
\bigcup_{j \in \mathbb{Z}} a^j E &= \bigcup_{j \in \mathbb{Z}} a^j b^{-1} F \\
&= b^{-1} \left( \bigcup_{j \in \mathbb{Z}} b a^j b^{-1} F \right) \\
&= b^{-1} b M = M.
\end{aligned}$$

Again, disjointness of the dilates is immediate. Thus, we have proven the following theorem, that seems to be well known:

**Theorem 1.15** ([15]). *Let  $M$  be a measurable subset of  $\mathbb{R}^n$  with positive measure satisfying  $aM = M$  for some expansive matrix  $a$ , and let  $\mathcal{T}$  be a full rank lattice in  $\mathbb{R}^n$ . Then, there exists a set  $E \subset M$  such that  $\{E + k \mid k \in \mathcal{T}\}$  tiles  $\mathbb{R}^n$  and  $\{a^j E \mid j \in \mathbb{Z}\}$  tiles  $M$ .*

Theorem 1.15 can be used to give an easy proof of Theorem 1.10 removing three of the assumptions, but adding the assumption that the translation set is a lattice.

**Theorem 1.16.** *Let  $\mathcal{D} \subset \text{GL}(n, \mathbb{R})$  be such that there exists a measurable set  $\Omega$  such that  $\{d^T \Omega \mid d \in \mathcal{D}\}$  is a tiling of  $\mathbb{R}^n$ . Suppose also that  $\mathcal{D}^T$  is a invariant for some expansive matrix  $a$ . Let  $\mathcal{T} \subset \mathbb{R}^n$  be a full-rank lattice. Then, there exists a  $(\mathcal{D}, \mathcal{T})$  wavelet set  $E$ .*

*Proof.* By assumption, there exists a set  $\Omega$  such that  $\mathcal{D}^T(\Omega)$  is a tiling of  $\mathbb{R}^n$ . Consider the set  $M = \bigcup_{j \in \mathbb{Z}} a^j \Omega$ . The set  $M$  is clearly  $a$  invariant, and  $\{a^j(\Omega) \mid j \in \mathbb{Z}\}$  is a measurable partition of  $M$  so by 1.15, there exists a set  $E$  such that  $\{a^j(E) \mid j \in \mathbb{Z}\}$  tiles  $M$  and  $\{E + k \mid k \in \mathcal{L}^*\}$  tiles  $\mathbb{R}^n$ . By Lemmas 1.11 and 1.12, since  $E$  is  $a$ -equivalent to  $\Omega$ ,  $\{d^T E \mid d \in \mathcal{D}\}$  tiles  $\mathbb{R}^n$ . That is,  $E$  is a  $(\mathcal{D}, \mathcal{T})$  wavelet set, as desired.  $\square$

We have exhibited above the essential nature of the argument in [56]. That is, what is desired is a general criterion for the following question:

**Question 5.** Given an expansive matrix  $a$ , a lattice  $\mathcal{L}$  and two sets  $\Omega_1$  and  $\Omega_2$ , when does there exist a set  $\Omega$  that is  $a$ -equivalent to  $\Omega_1$  and  $\mathcal{L}$  equivalent to  $\Omega_2$ ?

In the above case, we were forced to restrict to the case that  $\Omega_2$  is a fundamental region for the lattice  $\mathcal{L}$ , since that is what was shown in [15]. As a final generalization in this section, we show that what is really necessary is that  $\Omega_2$  contain a neighborhood of the origin. The reader should compare the theorem below with the statement and proofs of the theorems in [17] and [18].

**Theorem 1.17.** *Let  $a$  be an expansive matrix and  $\Omega_1 \subset \mathbb{R}^n$  a set of positive measure such that  $|a^j \Omega_1 \cap a^k \Omega_1| = 0$  whenever  $j \neq k$ . Let  $M = \bigcup_{j \in \mathbb{Z}} a^j \Omega_1$ . Let  $\mathcal{L} \subset \mathbb{R}^n$  be a full rank lattice and  $\Omega_2 \subset \mathbb{R}^n$  such that  $|\Omega_2 + k_1 \cap \Omega_2 + k_2| = 0$  for  $k_1 \neq k_2 \in \mathcal{L}$  and such that there exists  $\epsilon > 0$  such that  $M \cap B_\epsilon(0) \subset \Omega_2 \cap B_\epsilon(0)$ . Then, there exists a set  $\Omega$  such that  $\Omega$  is  $a$ -equivalent to  $\Omega_1$  and  $\mathcal{L}$  equivalent to  $\Omega_2$ .*

Before proving Theorem 1.17, we state and prove its main corollary, which is Theorem 2.1 of [56] with all but one technical assumption removed.

**Corollary 1.18.** *Let  $\mathcal{D} \subset \text{GL}(n, \mathbb{R})$  be such that  $\mathcal{D}^T$  is a multiplicatvie tiling set. Let  $\mathcal{T}$  be a spectrum with interior such that there exists a full rank lattice such that  $\mathcal{T} - \mathcal{T} \subset \mathcal{L}$ . Then, if  $\mathcal{D}^T$  is  $a$ -invariant for some expansive matrix  $a$ , there exists a  $(\mathcal{D}, \mathcal{T})$  wavelet set.*

*Proof.* Since translations of spectral sets are again spectral sets, we may assume without loss of generality that  $\Omega_2$  contains 0 as an interior point. By Lemma 3.1 of [56],  $(\Omega_2 + k_1) \cap (\Omega_2 + k_2)$  has measure 0 whenever  $k_1 \neq k_2 \in \mathcal{L}^*$ . So, by 1.17, there is a set  $\Omega$  that is  $a$  equivalent to  $\Omega_1$  and  $\mathcal{L}^*$  equivalent to  $\Omega_2$ . By Lemma 1.11,  $\{d^T \Omega \mid d \in \mathcal{D}\}$  tiles  $\mathbb{R}^n$ , and by Lemma 3.2 in [56],  $(\Omega, \mathcal{T})$  is a spectral set. Therefore,  $\Omega$  is a  $(\mathcal{D}, \mathcal{T})$  wavelet set.  $\square$

We turn now to proving Theorem 1.17. We begin by noting that arguing as in the proof of Theorem 1.15, one can restrict to the case that  $\mathcal{L} = \mathbb{Z}^n$ . Next, we need to extract the following lemma from the proof of Corollary 1 in [15], then we will follow very closely the proof in [18].

**Lemma 1.19.** *Let  $a$  be an expansive matrix in  $GL(n, \mathbb{R})$ . Let  $F_0$  be a set of positive measure such that  $|a^j F_0 \cap a^k F_0| = 0$  whenever  $j \neq k$ . Let  $E = [-1/2, 1/2]^n$ . Then, for every  $\epsilon > 0$ , there exists  $k_0 \in \mathbb{Z}$  and  $\ell_0 \in \mathbb{Z}^n$  such that  $|a^{k_0} F_0 \cap (E + \ell_0)| > 1 - \epsilon$ .*

The proof of Lemma 1.19 is a clever use of a Lebesgue density argument, which we will not repeat here.

*Proof of Theorem 1.17.* First, note that as in the case of Theorem 1.15, Lemma 1.19 is really a lemma about arbitrary full-rank lattices  $\mathcal{L}$ . Moreover, one can replace  $E = [-1/2, 1/2]^n$  by any subset  $E$  of a fundamental region of  $\mathcal{L}$  to get the following formally stronger lemma.

**Lemma 1.20.** *Let  $a$  be an expansive matrix in  $GL(n, \mathbb{R})$ . Let  $F_0$  be a set of positive measure such that  $|a^j F_0 \cap a^k F_0| = 0$  whenever  $j \neq k$ . Let  $\mathcal{L} \subset \mathbb{R}^n$  be a full-rank lattice with fundamental region  $\Omega$ . Then, for every set  $E \subset \Omega$  and every  $\epsilon > 0$ , there exists  $k_0 \in \mathbb{Z}$  and  $\ell_0 \in \mathcal{L}$  such that  $|a^{k_0} F_0 \cap (E + \ell_0)| \geq (1 - \epsilon)|E|$ .*

Turning to the proof of 1.17, note that by Theorem 1.13, we may assume without loss of generality that  $\Omega_1$  is bounded and bounded away from the origin. We may also assume that  $\Omega_2$  is contained in a convex, centrally symmetric fundamental region of  $\mathcal{L}$ . The rest of the proof follows very closely the proof of Theorem 3.7 in [18], with Lemma 1.20 playing the role of Proposition 3.5 in [18]. We will construct a family  $\{G_{ij} \mid i \in \mathbb{N}, j \in \{1, 2\}\}$  of measurable sets whose  $a$ -dilates form a measurable partition of  $\Omega_1$  and whose translates by vectors in  $\mathcal{L}$  form a measurable partition of  $\Omega_2$ . Then

$$(1.1) \quad \Omega := \bigcup G_{ij}$$

is the set desired in Theorem 1.17. Since the steps are so similar to [18], we will give the first step of the inductive definition, and the properties needed for induction. Details are the same as in [18].

Let  $\{\alpha_i\}$  and  $\{\beta_i\}$  be sequences of positive constants decreasing to 0 and such that  $\alpha_1 < \epsilon$  chosen so that  $B_{\alpha_1}(0) \cap M \subset B_{\alpha_1}(0) \cap \Omega_2$ . Let  $\tilde{E}_{11} = \Omega_2 \setminus B_{\alpha_1}(0)$ . Then,  $|\tilde{E}_{11}| > 0$ . Let  $\tilde{F}_{11}$  be a measurable subset of  $\Omega_1$  with measure strictly less than  $|\Omega_1|$ . By Lemma 1.20, there exists  $k_1 \in \mathbb{N}$  and  $\ell_1 \in \mathcal{L}$  such that

$$(1.2) \quad |a^{k_1} \tilde{F}_{11} \cap (\tilde{E}_{11} - \ell_1)| \geq \frac{1}{2} |\tilde{E}_{11}|$$

Let  $G_{11} := a^{k_1} \tilde{F}_{11} \cap (\tilde{E}_{11} - \ell_1)$ , let  $E_{11} := G_{11} + \ell_1$ , and let

$$(1.3) \quad F_{11} := \tilde{F}_{11} \cap a^{-k_1}(E_{11} - \ell_1) = a^{-k_1} G_{11}$$

Then  $F_{11} \subset \tilde{F}_{11} \subset \Omega_1$  and  $|\Omega_1 \setminus \tilde{F}_{11}| \geq |\Omega_1 \setminus F_{11}| > 0$ . Also,  $E_{11} \subset \tilde{E}_{11}$ , and

$$(1.4) \quad |E_{11}| = |G_{11}| \geq \frac{1}{2} |\tilde{E}_{11}|$$

Also,  $G_{11} = a^{k_1} F_{11}$ . Now choose  $F_{12} \subset \Omega_1$ , disjoint from  $F_{11}$ , such that  $\Omega_1 \setminus (F_{11} \cup F_{12})$  has positive measure less than  $\beta_1$ . Choose  $m_1$  such that  $a^{-m_1} F_{12}$  is contained in  $N_1 = B_{\alpha_1/2}(0)$  and is disjoint from  $G_{11}$ . (This is possible since  $G_{11}$  is bounded away from 0.) Set

$$(1.5) \quad G_{12} := E_{12} := a^{-m_1} F_{12}.$$

The first step is complete.

Proceed inductively, obtaining disjoint families of positive measure  $\{E_{ij}\}$  in  $\Omega_2$ ,  $\{F_{ij}\}$  in  $\Omega_1$  and  $\{G_{ij}\}$  such that for  $i = 1, 2, \dots$  and  $j = 1, 2$  we have

- (1)  $G_{i1} + \ell_i = E_{i1}$ ;
- (2)  $G_{i2} = E_{i2}$ ;
- (3)  $a^{-k_1} G_{i1} = F_{i1}$ ;
- (4)  $a^{m_i} G_{i2} = F_{i2}$ ;
- (5)  $|\Omega_1 \setminus (F_{11} \cup F_{12} \cup \dots \cup F_{i1} \cup F_{i2})| < \beta_i$ , and
- (6)  $|E_{i1}| \geq \frac{1}{2} |\Omega_2 \setminus (E_{11} \cup E_{12} \cup \dots \cup E_{i-1,1} \cup E_{i-1,2})| - \frac{1}{2} |N_i|$ , where  $N_i$  is a ball centered at 0 with radius less than  $\alpha_i$ .

Since  $\beta_i \rightarrow 0$ , item 5 implies that  $F \setminus (\bigcup F_{ij})$  is a null set, and since  $\alpha_i \rightarrow 0$ , item 6 implies that  $(E \setminus (\bigcup E_{ij}))$  is a null set. Let

$$(1.6) \quad F = \bigcup \{G_{ij} \mid i = 1, 2, \dots, j = 1, 2\}$$

then,  $G$  is congruent to  $\Omega_2$  by items 1 and 2, and the  $a$  dilates of  $G$  form a partition of  $M$ , as desired.  $\square$

For sets  $\mathcal{D} \subset GL(n, \mathbb{R})$  which are invariant under an expansive matrix, Theorem 1.18 is nice in that it reduces the question of existence of wavelet sets to the the question of existence of tiling sets for dilations and translations separately. It is still in some sense unsatisfactory, because it relies on the existence of objects external to the sets  $(\mathcal{D}, \mathcal{T})$  under consideration. From the point of view of characterizing sets  $(\mathcal{D}, \mathcal{T})$  for which wavelet sets exist, something more is needed. We will present in section 4 some progress on this question when  $\mathcal{D}$  is a countable subgroup of  $GL(n, \mathbb{R})$ .

## 2. ADMISSIBLE GROUPS AND FRAMES

We will now turn to the applications of those results to frames and wavelets in  $\mathbb{R}^n$ . But first we recall some results about the continuous wavelet transform.

Recall that translations and dilations on the real line form the so-called  $(ax + b)$ -group. Assume in general that we have a group  $G$  acting on a topological space. Assume that  $\mu$  is a Radon measure on  $X$  such that  $\mu$  is *quasi-invariant*, i.e., there exists a measurable function  $j : G \times X \rightarrow \mathbb{R}^+$  such that

$$\int_X f(g \cdot x) d\mu(x) = \int_X j(g, x) f(x) d\mu(x)$$

for all  $f \in L^1(X)$ . Then we can define a unitary representation of  $G$  on  $L^2(X)$  by

$$[\pi(g)f](x) = j(g^{-1}, x)^{-1/2} f(g^{-1}x).$$

For a fixed  $\psi \in L^2(G)$  define the transform  $W_\psi : L^2(X) \rightarrow C(G)$  by

$$W_\psi(f)(g) := (f, \pi(g)\psi)$$

and notice that  $W_\psi$  intertwines the representation  $\pi$  and the *left regular representation*, i.e.,

$$\begin{aligned} W_\psi(\pi(g)f)(x) &= (\pi(g)f, \pi(x)\psi) \\ &= (f, \pi(g^{-1}x)\psi) \\ &= W_\psi(f)(g^{-1}x). \end{aligned}$$

For the  $(ax + b)$ -group this becomes

$$(2.1) \quad W_\psi(f)(a, b) = (f \mid \pi(a, b)\psi) = |a|^{-1/2} \int_{\mathbb{R}} f(x) \overline{\psi((x-b)/a)} dx.$$

Here  $T_b : L^2(\mathbb{R}) \rightarrow L^2(\mathbb{R})$  stands for the unitary isomorphism corresponding to translation  $T_b f(x) = f(x - b)$  and  $D_a : L^2(\mathbb{R}) \rightarrow L^2(\mathbb{R})$  is the unitary map corresponding to dilation  $D_a f(x) = |a|^{-1/2} f(x/a)$ ,  $a \neq 0$ .

The discrete wavelet transform is obtained by sampling the wavelet transform, given by a suitable wavelet  $\psi$ , of a function  $f$  at points gotten by replacing the full  $(ax + b)$ -group by a discrete subset generated by translation by integers and dilations of the form  $a = 2^n$ :

$$\begin{aligned} W_\psi^d(f)(2^{-n}, -2^{-n}m) &= (f \mid \pi((2^n, m)^{-1})\psi) \\ &= 2^{n/2} \int_{\mathbb{R}} f(x) \overline{\psi(2^n x + m)} dx. \end{aligned}$$

Hence, the corresponding frame is

$$(2.2) \quad \{\pi((2^n, m)^{-1})\psi \mid n, m \in \mathbb{Z}\}.$$

The inverse refers here to the inverse in the  $(ax + b)$ -group.

In the same way it is well known, that the short time Fourier transform, and several other well known integral transforms have a common explanation in this way in the language of representation theory. This observation is the basis for the generalization of the continuous wavelet transform to higher dimensions and more general settings, and was already made by A. Grossmann, J. Morlet, and T. Paul in 1985, see [33, 34]. In [33] the connection to square integrable representations and the relation to the fundamental paper of M. Duflo and C. C. Moore [20] was already pointed out. Several natural questions arise now, in particular to describe the image of the transform  $W_\psi$  and how that depends on  $\psi$ . But we will not go into that here, but refer to [2, 3, 6, 8, 19, 21, 23, 24, 27, 29, 30, 31, 32, 33, 34, 38, 45, 50, 58] for discussion. Here, we will concentrate on the connection to frames, wavelets and wavelet sets.

Denote by  $\text{Aff}(\mathbb{R}^n)$  the group of invertible affine linear transformations on  $\mathbb{R}^n$ . Thus  $\text{Aff}(\mathbb{R}^n)$  consists of pairs  $(x, h)$  with  $h \in \text{GL}(n, \mathbb{R})$  and  $x \in \mathbb{R}^n$ . The action of  $(x, h) \in \text{Aff}(\mathbb{R}^n)$  on  $\mathbb{R}^n$  is given by

$$(x, h)(v) = h(v) + x.$$

The product of group elements is the composition of maps. Thus

$$(x, a)(y, b) = (a(y) + x, ab)$$

the identity element is  $e = (0, \text{id})$  and the inverse of  $(x, a) \in \text{Aff}(\mathbb{R}^n)$  is given by

$$(x, a)^{-1} = (-a^{-1}(x), a^{-1}).$$

Thus  $\text{Aff}(\mathbb{R}^n)$  is the semidirect product of the abelian group  $\mathbb{R}^n$  and the group  $\text{GL}(n, \mathbb{R})$ ;  $\text{Aff}(\mathbb{R}^n) = \mathbb{R}^n \times_s \text{GL}(n, \mathbb{R})$ . Let  $H \subset \text{GL}(n, \mathbb{R})$  be a closed subgroup. Define

$$\mathbb{R}^n \times_s H := \{(x, a) \in \text{Aff}(\mathbb{R}^n) \mid a \in H, x \in \mathbb{R}^n\}.$$

Then  $H \times_s \mathbb{R}^n$  is a closed subgroup of  $\text{Aff}(\mathbb{R}^n)$ .

Define a unitary representation of  $\mathbb{R}^n \times_s H$  on  $L^2(\mathbb{R}^n)$  by

$$(2.3) \quad [\pi(x, a)f](v) := |\det(a)|^{-1/2} f((x, a)^{-1}(v)) = |\det(a)|^{-1/2} f(a^{-1}(v - x)).$$

Write  $\psi_{x,a}$  for  $\pi(x, a)\psi$ . We will also need another action of  $H$  on  $\mathbb{R}^n$  by  $a \cdot \omega := (a^{-1})^T(\omega)$ . We denote by  $\hat{\pi}(x, a)$  the unitary action on  $L^2(\mathbb{R}^n)$  given by

$$(2.4) \quad \hat{\pi}(x, a)f(v) = \sqrt{|\det(a)|} e^{-2\pi i(x|v)} f(a^{-1} \cdot v) = \sqrt{|\det(a)|} e^{-2\pi i(x|v)} f(a^T(v)).$$

**Remark 2.1.** Some authors use the semidirect product  $H \times_s \mathbb{R}^n$  instead of  $\mathbb{R}^n \times_s H$ . Thus first the translation and then the linear map is applied, i.e.,  $(a, x)(v) = a(v + x)$ . In this notation the product becomes  $(a, x)(b, y) = (ab, ab(y) + a(x))$ , the inverse of  $(a, x)$  is  $(a, x)^{-1} = (a^{-1}, -ax)$ , and the wavelet representation is

$$\tilde{\pi}(a, x)f(v) = |\det a|^{-1/2} f(a^{-1}v - x).$$

The Fourier transform intertwines the representations  $\pi$  and  $\hat{\pi}$  [21], Lemma 3.1, i.e.,

$$(2.5) \quad \widehat{\pi(x, a)f}(\omega) = \hat{\pi}(x, a)\hat{f}(\omega), \quad f \in L^2(\mathbb{R}^n).$$

Denote by  $d\mu_H$  a left invariant measure on  $H$ . A left invariant measure on  $G$  is then given by  $d\mu_G(x, a) = |\det(a)|^{-1}d\mu_H(a)dx$ . Let  $f, \psi \in L^2(\mathbb{R}^n)$ . A simple calculation shows that

$$(2.6) \quad \int_G |(f | \pi(x, a)\psi)|^2 d\mu_G(x, a) = \int_{\mathbb{R}^n} |\hat{f}(\omega)|^2 \int_H |\hat{\psi}(a^{-1} \cdot \omega)|^2 d\mu_H(a) d\omega$$

$$(2.7) \quad = \int_{\mathbb{R}^n} |\hat{f}(\omega)|^2 \int_H |\hat{\psi}(a^T(\omega))|^2 d\mu_H(a) d\omega$$

There are several ways to read this. First let  $M \subseteq \mathbb{R}^n$  be measurable and invariant under the action  $H \times \mathbb{R}^n \ni (h, v) \mapsto h \cdot v := (h^{-1})^T(v) \in \mathbb{R}^n$ . Then we denote by  $L_M^2(\mathbb{R}^n)$  the space of function  $f \in L^2(\mathbb{R}^n)$  such that  $\hat{f}(\xi) = 0$  for almost all  $\xi \notin M$ . Notice that  $L_M^2(\mathbb{R}^n)$  is a closed invariant subspace, and that the orthogonal projection onto  $L_M^2(\mathbb{R}^n)$  is given by  $f \mapsto (\hat{f}\chi_M)^\vee$ . The first result is now:

**Theorem 2.2.** *Let  $M \subseteq \mathbb{R}^n$  be measurable of positive measure, and invariant under the action  $(a, v) \mapsto a \cdot v$ . Then the wavelet transform*

$$W_\psi : f \mapsto (f | \pi(x, a)\psi)_{L^2(\mathbb{R}^n)} = |\det a|^{-1/2} \int f(y) \overline{\psi(a^{-1}(y-x))} dy$$

*is a partial isometry  $W_\psi : L_M^2(\mathbb{R}^n) \rightarrow L^2(G)$  if and only if*

$$(2.8) \quad \Delta_\psi(\omega) := \int_H |\hat{\psi}(a^T \omega)|^2 d\mu_H(a) = 1$$

*for almost all  $\omega \in M$ .*

Following [45, 58] we define

**Definition 2.3** (Laugesen, Weaver, Weiss, and Wilson). Let  $M \subseteq \mathbb{R}^n$ , be measurable, invariant, and  $|M| > 0$ . Let  $\psi \in L^2(\mathbb{R}^n)$  then  $\psi$  is said to be a (normalized) admissible  $(H, M)$ -wavelet if for almost all  $\omega \in M$  we have

$$\int_H |\hat{\psi}(a^T \omega)|^2 d\mu_H(a) = 1.$$

We say that the pair  $(H, M)$  is *admissible* if a  $(H, M)$ -admissible wavelet  $\psi$  exists. If  $M = \mathbb{R}^n$  then we say that  $H$  is *admissible* and that  $\psi$  is a (normalized) *wavelet* function.

Assume that  $\psi$  is a normalized admissible wavelet. Then

$$G \ni (x, a) \mapsto F(x, a) := W_\psi f(x, a)\psi_{x, a} \in L^2(\mathbb{R}^n)$$

is well defined and if  $g \in L^2(\mathbb{R}^n)$  then

$$\begin{aligned} \int_G (F(x, a) | g)_{L^2(\mathbb{R}^n)} d\mu_G(x, a) &= \int_G W_\psi f(x, a) \left( \int_{\mathbb{R}^n} \psi_{x, a}(y) \overline{g(y)} dy \right) d\mu_G(x, a) \\ &= \int_G W_\psi f(x, a) \overline{W_\psi g(x, a)} d\mu_G(x, a) \\ &= (W_\psi f | W_\psi g)_{L^2(G)} \\ &= (f | g)_{L^2(\mathbb{R}^n)}. \end{aligned}$$

Hence

**Lemma 2.4.** Assume that  $\psi \in L^2(\mathbb{R}^n)$  satisfies  $\int_H |\hat{\psi}(a^T \omega)|^2 d\mu_H(a) = 1$ . Then

$$(2.9) \quad f = \int W_\psi f(x, a) \psi_{x,a} d\mu_G(x, a)$$

as a weak integral for all  $f \in L^2(\mathbb{R}^n)$ .

**Question 6** (Laugesen, Weaver, Weiss, and Wilson). Give a characterization of admissible subgroups of  $\mathrm{GL}(n, \mathbb{R})$ .

It is easy to derive one necessary condition for admissibility. For  $\omega \in \mathbb{R}^n$  let

$$(2.10) \quad H^\omega = \{h \in H \mid h \cdot \omega = \omega\} = \{h \in H \mid h^T(\omega) = \omega\}$$

be the stabilizer of  $\omega$ . Then admissibility implies that  $H$  is compact for almost all  $\omega \in \mathbb{R}^n$ . But this condition is not sufficient and there is by now *no* complete characterization of admissible group. The best result up to now is the following due to Laugesen, Weaver, Weiss, and Wilson [45]:

**Theorem 2.5** (Laugesen, Weaver, Weiss, and Wilson, [45]). Let  $H$  be a closed subgroup of  $\mathrm{GL}(n, \mathbb{R})$ . For  $\omega \in \mathbb{R}^n$  and  $\epsilon > 0$  let

$$H_\epsilon^\omega := \{h \in H \mid \|a \cdot \omega - \omega\| \leq \epsilon\}$$

be the  $\epsilon$ -stabilizer of  $\omega$ . If either

- (1)  $G = \mathbb{R}^n \times_s H$  is non-unimodular, or
- (2)  $\{\omega \in \mathbb{R}^n \mid H^\omega \text{ is non-compact}\}$  has positive Lebesgue measure

holds, then  $H$  is not admissible. If both (1) and

- (3)  $\{\omega \in \mathbb{R}^n \mid H^\omega \text{ is non-compact for all } \epsilon > 0\}$  has positive Lebesgue measure fail,

then  $H$  is admissible.

### 3. A SPECIAL CLASS OF GROUPS

In [21] and [50] a special class of groups with finitely many open orbits were discussed. Those were related to the so-called *prehomogeneous vector spaces of parabolic type* [9]. We start with a simple lemma:

**Lemma 3.1.** Let  $H \subset \mathrm{GL}(n, \mathbb{R})$  be a closed subgroup. Assume that  $M \subseteq \mathbb{R}^n$  is up to set of measure zero a union of finitely many open orbits  $U_1, \dots, U_k \subset \mathbb{R}^n$  under the action  $(a, \omega) \mapsto a \cdot \omega = (a^{-1})^T(\omega)$ . Assume furthermore that  $H^\omega$  is compact for  $\omega \in U_j$ ,  $j = 1, \dots, k$ . Then the pair  $(H, M)$  is admissible.

*Proof.* Fix  $\omega_j \in U_j$ . For  $j = 1, \dots, k$  let  $g_j \in C_c(U_j)$ ,  $g_j \geq 0$ ,  $g \neq 0$ . Then the function

$$H \ni a \mapsto g_j(a^T(\omega_j)) \in \mathbb{C}$$

has compact support and  $\int_H g_j(a^T(\omega_j)) d\mu_H(a) > 0$ . Let  $\omega \in U_j$ . Choose  $h \in H$  such that  $\omega = h^T(\omega_j)$ . This is possible because  $U_j$  is homogeneous under  $H$ . Then

$$\begin{aligned} \int_H g_j(a^T(\omega)) d\mu_H(a) &= \int_H g_j(a^T h^T(\omega_j)) d\mu_H(a) \\ &= \int_H g_j((ha)^T(\omega_j)) d\mu_H(a) \\ &= \int_H g_j(a^T(\omega_j)) d\mu_H(a). \end{aligned}$$

Hence  $\Delta_j = \int_H g_j(a^T(\omega)) d\mu_H(a) > 0$  is independent of  $\omega \in U_j$ . Define  $\varphi : \mathbb{R}^n \rightarrow \mathbb{C}$  by

$$\varphi(\omega) := \begin{cases} g_j(\omega)/\Delta_j & \text{if } \omega \in U_j \\ 0 & \text{if } \omega \notin \bigcup_{j=1}^k U_j \end{cases}.$$

Then  $\varphi \in C_c(\mathbb{R}^n)$ , so in particular  $\varphi \in L^2(\mathbb{R}^n)$ . Define  $\psi := \varphi^\vee$ . Then  $\psi$  satisfies the admissibility condition (2.8) and it follows that  $H$  is admissible.  $\square$

**Question 7.** Classify all the admissible group with finitely many open orbits of full measure.

**Lemma 3.2.** *Let  $H \subset \mathrm{GL}(n, \mathbb{R})$  be a closed subgroup such that  $H$  can be written as  $H = ANR = NAR = RAN$  with  $R$  compact,  $A$  simply connected abelian, and such that the map*

$$N \times A \times R \ni (n, a, r) \mapsto nar \in H$$

*is a diffeomorphism. Assume furthermore that  $R$  and  $A$  commute, and that  $R$  and  $A$  normalize  $N$ . Finally assume that there exists a co-compact discrete subgroup  $\Gamma_N \subset N$ . Let  $\Gamma_A \subset A$  be a co-compact subgroup in  $A$ . Choose bounded measurable subsets  $\mathbb{F}_A \subset A$ , and  $\mathbb{F}_N \subset N$  such that  $N = \Gamma_N \mathbb{F}_N$ , and  $A = \Gamma_A \mathbb{F}_A$  and such that the union is disjoint. Let  $\Gamma = \Gamma_A \Gamma_N$  and  $\mathbb{F}_H = \mathbb{F}_N \mathbb{F}_A R \subset H$ . Then we have*

$$H = \bigcup_{\gamma \in \Gamma} \gamma \mathbb{F}_H$$

*and the union is disjoint. Furthermore we can choose  $\mathbb{F}_H$  such that  $\mathbb{F}_H^\circ \neq \emptyset$ .*

*Proof.* We have

$$\begin{aligned} \bigcup_{\gamma} \gamma \mathbb{F}_N \mathbb{F}_A R &= \Gamma_A \Gamma_N (\mathbb{F}_N) \mathbb{F}_A R \\ &= \Gamma_A N \mathbb{F}_A R \quad \text{because } \Gamma_N \mathbb{F}_N = N \\ &= \bigcup_{\gamma \in \Gamma_A} (\gamma N \gamma^{-1}) \gamma \mathbb{F}_A R \\ &= \bigcup_{\gamma \in \Gamma_A} N \gamma \mathbb{F}_A R \quad \text{because } A \text{ normalizes } N \\ &= N \Gamma_A \mathbb{F}_A R \\ &= NAR \\ &= H. \end{aligned}$$

Assume now that

$$\gamma_A \gamma_N f_N f_A r = \sigma_A \sigma_N g_N g_A s$$

for some  $\gamma_A, \sigma_A \in \Gamma_A$ ,  $\gamma_N, \sigma_N \in \Gamma_N$ ,  $f_A, g_A \in \mathbb{F}_A$ ,  $f_N, g_N \in \mathbb{F}_N$ , and  $r, s \in R$ . Then, as  $A \times N \times R \ni (a, n, r) \mapsto anr \in H$  is a diffeomorphism, it follows that  $r = s$ . Hence  $\gamma_A \gamma_N f_N f_A = \sigma_A \sigma_N g_N g_A$ . But then – as  $A$  normalizes  $N$  –

$$\begin{aligned} \gamma_N f_N &= (\gamma_A^{-1} \sigma_A) \sigma_N g_N (g_A f_A^{-1}) \\ &= (\gamma_A^{-1} \sigma_A g_A f_A^{-1}) ((g_A f_A)^{-1} \sigma_N g_N (g_A f_A^{-1})) \end{aligned}$$

Hence  $\gamma_A^{-1} \sigma_A g_A f_A^{-1} = 1$  or

$$\gamma_A f_A = \sigma_A g_A.$$

As the union  $\Gamma_A \mathbb{F}_A$  is disjoint, it follows that  $\gamma_A = \sigma_A$  and  $f_A = g_A$ . But then the above implies that

$$\gamma_N f_N = \sigma_N g_N.$$

But then – again because the union is disjoint – it follows that  $\gamma_N = \sigma_N$  and  $f_N = g_N$ .  $\square$

Our first application of this theorem is to give a simple proof of the main result, Theorem 4.2, of [50], without using the results of [8]. We will reformulate those results so as to include sampling on irregular grids, see also [4]. Let us first recall some definition before we state the results.

**Definition 3.3.** Let  $\mathcal{H}$  be a separable Hilbert space, and let  $\mathbb{J}$  be a finite or countable infinite index set. A sequence  $\{f_j\}_{j \in \mathbb{J}}$  in  $\mathcal{H}$  is called a *frame* if there exists constants  $0 < A \leq B < \infty$  such that for all  $x \in \mathcal{H}$  we have.

$$A\|x\|^2 \leq \sum_{j \in \mathbb{J}} |(x, f_j)|^2 \leq B\|x\|^2.$$

$\{f_j\}_{j \in \mathbb{J}}$  is a *tight frame* if we can choose  $A = B$  and a *normalized tight frame* or *Parseval frame* if we can choose  $A = B = 1$ .

**Example 3.4.** Let  $\mathcal{H}$  be a Hilbert space and  $\mathcal{K} \subset \mathcal{H}$  a closed subspace. Assume that  $\{u_n\}$  is an orthonormal basis of  $\mathcal{H}$ . Let  $\text{pr} : \mathcal{H} \rightarrow \mathcal{K}$  be the orthogonal projection. Define  $f_j = \text{pr}(u_j)$ . Then  $\{f_j\}$  is a Parseval frame for  $\mathcal{K}$ . In fact it is easy to see that every Parseval frame can be constructed in this way. In particular we can apply this to the situation where  $(\Omega, \mathcal{T})$  is a spectral pair and  $M \subset \Omega$  is measurable with  $|M| > 0$ . Then  $\{|\Omega|^{-1/2}e_\lambda\}_{\lambda \in \mathcal{T}}$  is an orthonormal basis for  $L^2(\Omega)$  and hence  $\{f_\lambda := |\Omega|^{-1/2}e_\lambda|_M\}_{\lambda \in \mathcal{T}}$  is a Parseval frame for  $L^2(M)$ .

Assume now that  $H = ANR$  satisfies the conditions in Lemma 3.2. Let  $\Gamma = \Gamma_A \Gamma_N$  and  $\mathbb{F}_H = \mathbb{F}_N \mathbb{F}_A R$  be as in that Lemma. Suppose that  $M \subseteq \mathbb{R}^n$  is  $H$  invariant and such that there are finitely many open orbits  $U_1, \dots, U_k \subseteq M$  such that  $|M \setminus \bigcup_{j=1}^k U_j| = 0$ . Finally we assume that for each  $\omega_j \in U_j$  the stabilizer of  $\omega_j$  in  $H$  under the action  $(h, \omega) \mapsto (h^{-1})^T(\omega)$  is contained in  $R$  and hence compact. Let  $\mathbb{F}_j = F_H \cdot \omega_j$  and  $\mathbb{F} = \bigcup_{j=1}^k \mathbb{F}_j$ . Then the Lemma 3.2 implies that we have a multiplicative tiling of  $M$  as

$$(3.1) \quad M = \bigcup_{\gamma \in \Gamma} \gamma \cdot \mathbb{F} = \bigcup_{\gamma \in \Gamma^{-1}} \gamma^T(\mathbb{F})$$

(up to set of measure zero). If  $f : \mathbb{R}^n \rightarrow \mathbb{C}$  is a function and  $a \in \text{GL}(n, \mathbb{R})$  let  $L_a f(x) := f(a^{-1}x)$ .

**Theorem 3.5.** Let the notation be as above. Suppose that  $\{e_t|_{\mathbb{F}}\}_{t \in \mathcal{T}}$  is a frame for  $L^2(\mathbb{F})$ . Let  $\varphi = \chi_{\mathbb{F}}^\vee$ . Then the sequence  $\{\pi((t, \gamma)^{-1})\varphi\}_{(t, \gamma) \in \mathcal{T} \times \Gamma}$  is a frame for  $L^2(M)$  with the same frame bounds. In particular  $\{\pi((t, \gamma)^{-1})\varphi\}_{(t, \gamma) \in \mathcal{T} \times \Gamma}$  is a Parseval frame for  $L_M^2(\mathbb{R}^n)$  if and only if  $\{e_t|_{\mathbb{F}}\}_{t \in \mathcal{T}}$  is a Parseval frame for  $L^2(\mathbb{F})$ .

*Proof.* This follows from the fact that by (3.1) we have

$$L_M^2(\mathbb{R}^n) \simeq L^2(M) \simeq \bigoplus_{\gamma \in \Gamma^{-1}} L^2(\gamma^T \mathbb{F})$$

where the first isomorphism is given by the Fourier transform.  $\square$

Notice, that we can always find a sequence  $\{ce_t|_{\mathbb{F}}\}$ ,  $c > 0$ , which is a Parseval frame for  $L^2(M)$  by taking a spectral pair  $(\Omega, \mathcal{T})$ , such that  $\mathbb{F} \subset \Omega$ , i.e., a parallelepiped  $\Omega$ .

There are several ways to state different versions of the above theorem. In particular one can have different groups  $H_j = A_j N_j R_j$ , with compact stabilizers, such that each of them has finitely many open orbits,  $U_{j,1}, \dots, U_{j,k_j}$  such that  $\mathbb{R}^n = \bigcup_{j,l} \Gamma_j U_{j,l}$  a disjoint union. But we will not state all those obvious generalizations, but only notice the following construction from [21]. We refer to the Appendix for more details. In [21] the authors started with a prehomogeneous vector space  $(L, V)$  of parabolic type, see [9] for details. Then  $L$  has finitely many open orbits in  $V$ , but in general the stabilizer of a point is not compact. To deal with that, the authors constructed for each orbit  $U_j$  a subgroup  $H_j = A_j N_j R_j$  such that  $U_j$  is up to measure zero a disjoint union of open  $H_j$  orbits  $U_{j,i}$ . It turns out, that it is not necessary to pick a different group for each orbit, the same group  $H = H_j$  works for all the orbits.

**Theorem 3.6.** Let  $H = ANR$  be one of the group constructed in [21]. Then  $H$  is admissible.

*Proof.* This follows from Theorem 3.6.3 and Corollary 3.6.4 in [9].  $\square$

**Remark 3.7.** The statement in [9] is in fact stronger than the above remark. In most cases the group  $AN$  has finitely many open orbits. This group acts freely and is therefore admissible. The only exception is the so-called Type III spaces, where the group  $ANR$  has one orbit and is admissible.

**Example 3.8** ( $\mathbb{R}^+\text{SO}(n)$ ). Take  $A = \mathbb{R}^+\text{id}$ ,  $R = \text{SO}(n)$ , the group of orientation preserving rotations in  $\mathbb{R}^n$ , and  $N = \{\text{id}\}$ . Then  $H = \mathbb{R}^+\text{SO}(n)$  is the group of dilations and orientation preserving rotations. Notice that  $g^{-1} = g^T$  if  $g \in \text{SO}(n)$  and therefore  $g \cdot \omega = g(\omega)$ . The group  $H$  has two orbits  $\{0\}$  and  $\mathbb{R}^n \setminus \{0\}$ . The stabilizer of  $e_1 = (1, 0, \dots, 0)^T$  is isomorphic to  $\text{SO}(n-1)$ . In particular the stabilizer group is compact. It follows that  $\mathbb{R}^+\text{SO}(n)$  is admissible. In fact any function with compact support in  $\mathbb{R}^n \setminus \{0\}$  is, up to normalization, the Fourier transform of a admissible wavelet.

**Example 3.9** (Diagonal matrices). Let  $H$  be the group of diagonal matrices  $H = \{d(\lambda_1, \dots, \lambda_n) \mid \lambda_j \neq 0\}$ . Thus  $A = \{d(\lambda_1, \dots, \lambda_n) \mid \forall j : \lambda_j > 0\}$  and  $R = \{d(\epsilon_1, \dots, \epsilon_n) \mid \epsilon_j = \pm 1\}$ . The group  $N$  is trivial. Then  $H$  has one open and dense orbit

$$U = \{(x_1, \dots, x_n)^T \mid (j = 1, \dots, n) x_j \neq 0\} = H \cdot (1, \dots, 1)^T.$$

The stabilizer of  $(1, \dots, 1)^T$  is trivial and hence compact. It follows that  $H$  is admissible. We can also replace  $H$  by the connected group  $A$ . Then we have  $2^n$  open orbits parametrized by  $\epsilon \in \{-1, 1\}^2$

$$U_\epsilon = \{(x_1, \dots, x_j)^T \mid \text{sign}(x_j) = \epsilon_j\} = H \cdot (\epsilon_1, \dots, \epsilon_n).$$

The stabilizers are still compact and hence  $H$  is admissible.

**Example 3.10** (Upper triangular matrices). Let  $H$  be the group of upper triangular  $2 \times 2$ -matrices of determinant 1,

$$H = \left\{ \begin{pmatrix} a & t \\ 0 & 1/a \end{pmatrix} \mid a \neq 0, t \in \mathbb{R} \right\}.$$

Here  $A$  is the group of diagonal matrices with  $a > 0$ ,  $N$  is the group up upper triangular matrices with 1 on the main diagonal and  $R = \{\pm \text{id}\}$ , Then we have one open orbit of full measure given by

$$U = \{(x, y)^T \mid y \neq 0\} = H \cdot e_2$$

where  $e_2 = (0, 1)^T$ . The stabilizer of  $e_2$  is trivial which implies that  $H$  is admissible.

#### 4. CONSTRUCTION OF WAVELET SETS

We apply now our construction in section 1 to discrete subgroups of  $\text{GL}(n, \mathbb{R})$ . We start by the following reformulation of Theorem 2.5 for discrete groups. Our aim is later to apply it to the discrete subgroup  $\Gamma_A$  from the last section. As before we use the notation  $a \cdot x = (a^{-1})^T(x)$ .

**Lemma 4.1.** *Let  $D$  be a discrete subgroup  $\text{GL}(n, \mathbb{R})$ . If for almost every  $x \in \mathbb{R}^n$ , there exists an  $\epsilon > 0$  such that  $D_\epsilon^x$  is finite, then there exists a measurable function  $h$  such that*

$$(4.1) \quad \sum_{d \in D} |h(d^T x)|^2 = 1 \quad \text{a.e.}$$

We have the following improvement of Lemma 4.1.

**Proposition 4.2.** *Let  $D$  be a discrete subgroup  $\text{GL}(n, \mathbb{R})$ . If for almost every  $x \in \mathbb{R}^n$ , there exists an  $\epsilon > 0$  such that  $D_\epsilon^x$  is finite, then there exists a measurable function  $g$  of the form  $g = \chi_K$  such that*

$$(4.2) \quad \sum_{d \in D} |g(d^T x)|^2 = 1 \quad \text{a.e.}$$

*Proof.* We first recall some notation and preliminary results from [45]. For an open ball  $B \subset \mathbb{R}^n$ , we define the orbit density function  $f_B : \mathbb{R}^n \rightarrow [0, \infty]$  by

$$(4.3) \quad f_B(x) = \mu(\{d \in D \mid d^T x \in \overline{B}\}),$$

where  $\mu$  is counting measure. Lemma 2.6 of [45] asserts that

$$(4.4) \quad \Omega_0 := \{x \in \mathbb{R}^n \mid D_\epsilon^x \text{ non-compact } \forall \epsilon > 0\} = \{x \in \mathbb{R}^n \mid f_B(x) = \infty, \forall B : B \cap \mathcal{O}_x \neq \emptyset\}$$

Now, let  $\mathcal{B} = \{B_j\}$ ,  $j \in \mathbb{N}$ , be an enumeration of the balls in  $\mathbb{R}^n$  having rational centers and positive rational radii. Let  $F_j = F_{B_j}$ . We claim that

$$(4.5) \quad \mathbb{R}^n = \bigcup_{j \geq 1} \{x \in \mathbb{R}^n \mid f_j(x) = 1\} \bigcup \Omega \bigcup N,$$

where

$$(4.6) \quad N := \bigcup_{d \in D, d \neq \text{id}} \{x \in \mathbb{R}^n \mid d^T x = x\}.$$

To see this, suppose that  $x \notin (\Omega_0 \bigcup N)$ . Then, there exists an open ball  $B$  such that  $B \cap \mathcal{O}_x \neq \emptyset$ , and  $f_B(x) < \infty$ . Since  $B \cap \mathcal{O}_x \neq \emptyset$ , there is a  $d_0 \in D$  such that  $d_0^T x \in B$ . Therefore, there is a  $j$  such that  $d_0^T x \in B_j \subset B$ ; in particular  $B_j \cap \mathcal{O}_x \neq \emptyset$  and  $\infty > f_j(x) > 0$ . Now, write  $\{d \in D, d^T x \in \overline{B_j}\} = \{d_0^T, \dots, d_k^T\}$ . Since  $x \notin N$ , the  $d_i^T x = d_j^T x$  only if  $i = j$ . Hence, there is an open set  $O$  such that  $\mu(\{d \in D \mid d^T x \in O\}) = 1$ . Choose  $j$  such that  $d_0^T x \in B_j \subset O$  so that  $f_j(x) = 1$ .

Continuing along the lines of [45], let

$$\Omega_1 = \{x \in \mathbb{R}^n \mid f_1(x) = 1\}$$

and

$$\Omega_j = \{x \in \mathbb{R}^n \mid f_j(x) = 1\} \setminus (\Omega_1 \bigcup \dots \bigcup \Omega_{j-1})$$

The sets  $\{\Omega_j\}_{j \geq 1}$  form a disjoint collection of Borel sets such that  $\mathbb{R}^n \setminus (\bigcup_{j=1}^\infty \Omega_j)$  has measure 0 (it is a subset of  $\Omega \bigcup N$ ). Let us define

$$(4.7) \quad g(x) = \sum_{j=1}^\infty \chi_{\Omega_j}(x) \chi_{\overline{B_j}}(x)$$

and  $g(x) = 0$  for  $x \notin (\bigcup_{j \geq 1} \Omega_j)$ . Note that

$$(4.8) \quad g(x) = \chi_K, \quad K = \bigcup_{j=1}^\infty (\Omega_j \cap \overline{B_j}),$$

so all that is needed to complete the proof is to show  $\{d^T K \mid d \in D\}$  is a tiling of  $\mathbb{R}^n$ , equivalently,  $\sum_{d \in D} g(d^T x) = 1$  a.e. This is a special case of the argument in [45], which we outline now.

First, note that if  $x \in \mathbb{R}^n$  such that  $f_j(x) = 1$  for some smallest  $j$ , then there is a unique  $d \in D$  such that  $dx \in \overline{B_j}$ . Since  $f_j$  is constant on orbits,  $d^T x \in \Omega_j \cap \overline{B_j}$  and  $d^T x \notin (\Omega_1 \bigcup \dots \bigcup \Omega_{j-1})$ . Therefore,  $x \in d \cdot K$  and  $\bigcup_{d \in D} d^T K = \mathbb{R}^n$  up to a set of measure 0.

For disjointness, since  $d^T \Omega_j = \Omega_j$ , it suffices to check that  $(\Omega_j \cap \overline{B_j}) \cap (\Omega_j \cap \overline{B_j})a$  has measure 0 for all  $d$  not the identity  $\text{id}$ . If  $x \in (\Omega_j \cap \overline{B_j})$ , then  $f_j(x) = 1$ . If, in addition,  $x = d^T \omega$  for some  $\omega \in (\Omega_j \cap \overline{B_j})$ , then  $d^{-1}x \in \overline{B_j}$  which means that  $d \cdot x = x$  and  $d = \text{id}$  since  $f_j(x) = 1$ .  $\square$

**Theorem 4.3.** *Let  $D$  be a discrete subgroup  $\text{GL}(n, \mathbb{R})$  that contains an expansive matrix, and  $\mathcal{L} \subset \mathbb{R}^n$  a full-rank lattice. Then, there exists a  $(D, \mathcal{L})$  wavelet set.*

*Proof.* By Proposition 4.2, there exists a function  $g = \chi_K$  such that equation 4.2 holds. Therefore,  $\{d^T K \mid d \in D\}$  tiles  $\mathbb{R}^n$ . Thus, by Theorem 1.16 that there exists a  $(D, \mathcal{L})$  wavelet set.  $\square$

One final comment is that in all of the above considerations, the set  $D$  is assumed to be invariant under multiplication by an expansive matrix. Removing this condition seems to be very hard. Indeed, even when the set  $D = \{a^j \mid j \in \mathbb{Z}\}$ , it is not clear what happens when  $a$  is not an expansive matrix. In this case, the interplay between dilations and translations becomes crucial in understanding when there exists a wavelet set. For example, let  $a = \begin{pmatrix} 2 & 0 \\ 0 & 2/3 \end{pmatrix}$ ,  $D = \{a^j \mid j \in \mathbb{Z}\}$ , and  $\mathcal{T} = \mathbb{Z}^2$ . It is easy to see that there is a set of finite measure  $\Omega$  such that  $\{a^j \Omega\}$  tiles  $\mathbb{R}^2$ . However, there exist lattices  $\mathcal{L}_1$  and  $\mathcal{L}_2$  such that there are no  $(D, \mathcal{L}_1)$  wavelet sets, yet there are  $(D, \mathcal{L}_2)$  wavelet sets [53]. Hence, in the non-expansive case, it is not enough to simply prove the existence of sets that tile via dilations and translations separately.

We will now apply this to the discrete subgroup  $\Gamma_A \subset A$  from the last section, where  $A$  is as in Theorem 3.6.

**Theorem 4.4.** *Let  $H = ANR$  be one of the groups constructed in [21]. Then the following holds: The group  $A$  contains a discrete co-compact subgroup  $\Gamma_A \subset A$  such that  $E_A = \{d \in \Gamma_A \mid d \text{ is expansive}\}$  is a non-trivial subsemigroup. In particular there exists an expansive matrix  $a$  such that  $\Gamma_A$  is  $a$ -invariant. Let  $\Gamma_A$  and  $\Gamma_A^+$  be as in the Appendix and let  $\Gamma = \Gamma_A \Gamma_N$ . Then  $\Gamma \Gamma_A^+ \subset \Gamma$ .*

*Proof.* (1) follows from Lemma 5.3 in the appendix. For (2) we recall that  $\Gamma_A^+$  is contained in the center of  $ANR$ . Hence

$$\begin{aligned} \Gamma \Gamma_A^+ &= \Gamma_A \Gamma_N \Gamma_A^+ \\ &= \Gamma_A \Gamma_A^+ \Gamma_N \\ &\subset \Gamma_A \Gamma_N = \Gamma. \end{aligned}$$

□

We have now proved, using Theorem 4.3 the following theorem:

**Theorem 4.5.** *Let the notation be as in Theorem 4.4. Let  $\mathcal{L}$  be a full rank lattice in  $\mathbb{R}^n$ . Then there exists a  $(\Gamma_A, \mathcal{L})$  wavelet set and a  $(\Gamma, \mathcal{L})$  wavelet set.*

This Theorem gives several examples of non-groups of dilations for which wavelet sets exist. Unfortunately from the point of view characterizing sets  $(\mathcal{D}, \mathcal{T})$  for which wavelet sets exist, if one starts with the set  $\mathcal{D}$ , one still has to rely on the existence of an object external to the set  $\mathcal{D}$  for the existence of wavelet sets. It would also be interesting to remove the condition that  $\mathcal{L}$  is a lattice.

## 5. SYMMETRIC CONES

In this section we discuss the important example of homogeneous cones in  $\mathbb{R}^n$ . Those cones show up in several places in analysis. As an example one can take Hardy spaces of holomorphic function on tube type domains  $\mathbb{R}^n + i \oplus \Omega$  [54]. An excellent reference for harmonic analysis on symmetric cones is the book by J. Faraut and A. Koranyi [22]. A nonempty open subset  $\Omega \subset \mathbb{R}^n$  is called an *open (convex) cone* if  $\Omega$  is convex and  $\mathbb{R}^+ \Omega \subseteq \Omega$ . Let  $\Omega$  be an open cone, define the *dual cone*  $\Omega^*$  by

$$\Omega^* := \{v \in \mathbb{R}^n \mid \forall u \in \overline{\Omega} \setminus \{0\} : (v, u) > 0\}.$$

If  $\Omega^*$  is nonempty, then  $\Omega^*$  is an open cone.  $\Omega$  is *self-dual* if  $\Omega = \Omega^*$ . Let

$$\text{GL}(\Omega) = \{g \in \text{GL}(n, \mathbb{R}) \mid g(\Omega) = \Omega\}.$$

Then  $\Omega$  is *homogeneous* if  $\text{GL}(\Omega)$  acts transitively on  $\Omega$ . From now on we assume that  $\Omega$  is a self-dual homogeneous cone. Let  $g \in \text{GL}(\Omega)$  and  $u \in \overline{\Omega} \setminus \{0\}$ . Then  $g(u) \in \overline{\Omega} \setminus \{0\}$ . Hence if  $v \in \Omega = \Omega^*$ , then

$$(g^T(v), u) = (v, g(u)) > 0.$$

Thus  $g^T(v) \in \Omega^* = \Omega$ . It follows that  $\mathrm{GL}(\Omega)$  is invariant under transposition, and hence reductive. Let  $e \in \Omega$ . Then

$$K = \mathrm{GL}(\Omega)^e = \{g \in \mathrm{GL}(\Omega) \mid g(e) = e\}.$$

Let  $\theta(g) = (g^{-1})^T$ . Then it is always possible to choose  $e$  such that  $K = \{g \in \mathrm{GL}(\Omega) \mid \theta(g) = g\} = \mathrm{SO}(n) \cap \mathrm{GL}(n, \mathbb{R})$ . Define the *Lie algebra* of  $\mathrm{GL}(\Omega)$  by

$$\mathfrak{gl}(\Omega) := \{X \in M(n, \mathbb{R}) \mid \forall t \in \mathbb{R} : e^{tX} \in \mathrm{GL}(\Omega)\}.$$

Then  $\mathfrak{gl}(\Omega)$  is invariant under the Lie algebra automorphism  $\dot{\theta}(X) = -X^T$ . Let

$$\mathfrak{k} = \{X \in \mathfrak{gl}(\Omega) \mid \dot{\theta}(X) = X\}$$

and

$$\mathfrak{s} = \{X \in \mathfrak{gl}(\Omega) \mid \dot{\theta}(X) = -X\} = \mathrm{Symm}(n, \mathbb{R}) \cap \mathfrak{gl}(\Omega)$$

where  $\mathrm{Symm}(n, \mathbb{R})$  stand for the space of symmetric matrices. Let  $\mathfrak{a}$  be a maximal subspace in  $\mathfrak{s}$  such that  $[X, Y] = XY - YX = 0$  for all  $X, Y \in \mathfrak{a}$ . Notice that  $(X, Y) = \mathrm{Tr}(XY^T)$  is an inner product on  $\mathfrak{gl}(\Omega)$  and that, with respect to this inner product,  $\mathrm{ad}(X) : \mathfrak{gl}(\Omega) \rightarrow \mathfrak{gl}(\Omega)$ ,  $Y \mapsto [X, Y]$  satisfies

$$\mathrm{ad}(X)^T = \mathrm{ad}(X^T).$$

Hence the algebra  $\{\mathrm{ad}(X) \mid X \in \mathfrak{a}\}$  is a commuting family of self adjoint operator on the finite dimensional vector space  $\mathfrak{gl}(\Omega)$ . Hence there exists a basis  $\{X_j\}_j$  of  $\mathfrak{gl}(\Omega)$  consisting of joint eigenvectors of  $\{\mathrm{ad}(X) \mid X \in \mathfrak{a}\}$ . Let  $\mathfrak{z}(\mathfrak{a})$  be the zero eigenspace, i.e., the maximal subspace of  $\mathfrak{gl}(\Omega)$  commuting with all  $X \in \mathfrak{a}$ . Then there exists a finite subset  $\Delta \subset \mathfrak{a}^* \setminus \{0\}$  such that with

$$\mathfrak{gl}(\Omega)^\alpha = \{Y \in \mathfrak{gl}(\Omega) \mid \forall X \in \mathfrak{a} : \mathrm{ad}(X)Y = \alpha(X)Y\}$$

we have

$$\mathfrak{gl}(\Omega) = \mathfrak{z}(\mathfrak{a}) \oplus \bigoplus_{\alpha \in \Delta} \mathfrak{gl}(\Omega)^\alpha.$$

Notice that if  $\alpha \in \Delta$  then  $-\alpha \in \Delta$ . In fact, if

$$(5.1) \quad X \in \mathfrak{gl}(\Omega)^\alpha \implies X^T \in \mathfrak{gl}(\Omega)^{-\alpha}.$$

Let  $\mathfrak{a}' = \{X \in \mathfrak{a} \mid \forall \alpha \in \Delta : \alpha(X) \neq 0\}$ . Then  $\mathfrak{a}'$  is open and dense in  $\mathfrak{a}$ . In particular  $\mathfrak{a}' \neq \{0\}$ . Fix  $Z \in \mathfrak{a}'$  and let  $\Delta^+ = \{\alpha \in \Delta \mid \alpha(Z) > 0\}$ . Then  $\Delta = \Delta^+ \cup -\Delta^+$ , and if  $\alpha, \beta \in \Delta^+$  are such that  $\alpha + \beta \in \Delta$ , then  $\alpha + \beta \in \Delta^+$ . Let

$$\mathfrak{n} = \bigoplus_{\alpha \in \Delta^+} \mathfrak{gl}(\Omega)^\alpha.$$

Then  $\mathfrak{n}$  is a nilpotent Lie algebra and  $[\mathfrak{a}, \mathfrak{n}] \subseteq \mathfrak{n}$ . In particular it follows that  $\mathfrak{q} = \mathfrak{a} \oplus \mathfrak{n}$  is a solvable Lie algebra. Notice that the algebra  $\mathfrak{z}(\mathfrak{a})$  is invariant under transposition. Hence  $\mathfrak{z}(\mathfrak{a}) = \mathfrak{z}(\mathfrak{a}) \cap \mathfrak{k} \oplus \mathfrak{a}$ . Because of (5.1) it therefore follows that

$$\mathfrak{gl}(\Omega) = \mathfrak{k} \oplus \mathfrak{a} \oplus \mathfrak{n}.$$

This decomposition is called *the Iwasawa decomposition of  $\mathfrak{gl}(\Omega)$* . Let  $A = \{e^X \mid X \in \mathfrak{a}\}$  and  $N = \{e^Y \mid Y \in \mathfrak{n}\}$ . Then  $A$  and  $N$  are Lie groups,  $A$  is abelian, and  $aNa^{-1} = N$  for all  $a \in A$ . It follows that  $Q := AN = NA$  is a Lie group with  $N$  a normal subgroup. Furthermore we have the following *Iwasawa decomposition of  $\mathrm{GL}(\Omega)$* :

**Lemma 5.1** (The Iwasawa decomposition). *The map*

$$A \times N \times K \ni (a, n, k) \mapsto ank \in \mathrm{GL}(\Omega)$$

*is an analytic diffeomorphism.*

We note that the one dimensional group  $Z = \mathbb{R}^+ \text{id}$  is a subgroup of  $\text{GL}(\Omega)$  and in fact  $Z \subset A$ . If  $a(\lambda) = \lambda \text{id} \in Z$ , with  $\lambda > 1$ , then  $a(\lambda)$  is expansive. In particular it follows that the set  $E$  of expansive matrices in  $A$  is a nonempty subsemigroup of  $A$ . Let  $X_0 = \text{id}$ ,  $X_1, \dots, X_r$  be a basis of  $\mathfrak{a}$  and let

$$\Gamma_A = \{\exp(n_0 X_0 + \dots + n_r X_r) \mid n_j \in \mathbb{Z}\}.$$

Then  $A/\Gamma_A$  is compact. Furthermore there exists a discrete subgroup  $\Gamma_N \subset N$  such that  $N/\Gamma_N$  is compact.

Let now  $\mathcal{D} = \Gamma$  and  $d = \exp(2X_0)$ . Then  $d$  is expansive and  $d\mathcal{D} = \mathcal{D}d \subset \mathcal{D}$ , because  $d$  is central in  $\text{GL}(\Omega)$ . It follows that the results from the previous sections are applicable in this case.

#### APPENDIX: PREHOMOGENEOUS VECTOR SPACES

One way to find admissible groups with finitely many open orbits is to start with *prehomogeneous vector spaces*. Those are pairs  $(H, V)$  where  $H$  is a reductive Lie group, say  $H^T = H$ , and  $V$  is a finite dimensional vector spaces, such that  $H$  has finitely many open orbits in  $V$ . There is no full classification of those spaces at the moment, but a subclass, the *prehomogeneous vector spaces of parabolic type* has been classified. We refer to [9] Section 2.11, for detailed discussion and references. The problem, from the point of view of our work is, that the compact stabilizer condition does not hold in general, but as shown in [21] one can always replace  $H$  by a subgroup of the form  $ANR$  as before, such that  $ANR$  is admissible. Notice that, by using either  $ANR$  or  $A^T N^T R^T$ , which satisfies the same conditions, we can consider either the standard action on  $\mathbb{R}^n$  or the action  $(a, x) \mapsto (a^{-1})^T(x)$ . We will use the second action in what follows.

Let  $H = H^T$  be a reductive Lie group acting on  $V = \mathbb{R}^n$ . Then  $H$  can be written as  $H = LC$  where  $C = C^T$  is a vector group, isomorphic to a abelian subalgebra  $\mathfrak{c}$  of  $\mathfrak{gl}(n, \mathbb{R}) = M(n, \mathbb{R})$ . The isomorphism is simply given by the matrix exponential function

$$X \mapsto \exp(X) = e^X = \sum_{j=0}^{\infty} \frac{X^j}{j!}.$$

The vectorspace  $V$  is graded in the sense that there exists a subset  $\Delta \subset \mathfrak{c}^*$  such that

$$(5.2) \quad V = \bigoplus_{\alpha \in \Delta} V_{\alpha}$$

where

$$(5.3) \quad V_{\alpha} = \{v \in V \mid (\forall \alpha \in \mathfrak{c}) : X \cdot v = \alpha(X)v\}.$$

If  $c = \exp(X) \in C$  and  $\lambda \in \mathfrak{c}^*$ , then we write  $c^{\lambda} = e^{\lambda(X)}$ . In particular  $c \cdot v = c^{\alpha}v$  for all  $v \in V_{\alpha}$ .

Denote by  $\text{pr}_{\alpha}$  the projection onto  $V_{\alpha}$  along  $\bigoplus_{\beta \neq \alpha} V_{\beta}$ .

**Lemma 5.2.** *We have  $H \cdot V_{\alpha} \subset V_{\alpha}$  for all  $\alpha \in \Delta$ . Furthermore if  $v \in V$  and  $H \cdot v$  is open, then  $\text{pr}_{\alpha}(v) \neq 0$  for all  $\alpha \in \Delta$ .*

*Proof.* Let  $c \in C$ ,  $h \in H$  and  $v \in V_{\alpha}$ . As  $C$  is central in  $C$  it follows that  $c \cdot (h \cdot v) = h \cdot (c \cdot v) = c^{\alpha} h \cdot v$ .  $\square$

The set  $\Delta$  has the properties that  $0 \notin \Delta$ , if  $\alpha \in \Delta$ , then  $-\alpha \notin \Delta$ , and finally there exists  $\alpha_1, \dots, \alpha_k \in \Delta$  such that if  $\alpha \in \Delta$ , then there are  $n_1, \dots, n_r \in \mathbb{N}_0$  such that

$$(5.4) \quad \alpha = n_1 \alpha_1 + \dots + n_r \alpha_r.$$

For  $\alpha \in \Delta$  let  $\mathcal{N}_{\alpha} = \{X \in \mathfrak{c} \mid \alpha(X) = 0\}$ . Then  $\bigcup_{\alpha \in \Delta} \mathcal{N}_{\alpha}$  is a finite union of hyperplanes and hence the complement is open and dense in  $\mathfrak{c}$ . Let  $\mathfrak{c}^+$  be a connected component of the complement of  $\bigcup \mathcal{N}_{\alpha}$ . Because of (5.4) we can choose  $\mathfrak{c}^+$  such that

$$(5.5) \quad \forall X \in \mathfrak{c}^+ \forall \alpha \in \Delta : \alpha(X) > 0.$$

Notice that  $\mathfrak{c}^+$  is convex,  $\mathfrak{c}^+ + \mathfrak{c}^+ \subset \mathfrak{c}^+$  and  $\mathbb{R}^+ \mathfrak{c}^+ \subset \mathfrak{c}^+$ .

**Lemma 5.3.** *The group  $A$  contains a non-trivial abelian semigroup of expanding matrices.*

*Proof.* Let  $C^+ := \exp(\mathfrak{c}^+)$ . Suppose that  $a, b \in C^+$ . Choose  $X, Y \in \mathfrak{c}^+$  such that  $a = \exp(X)$  and  $b = \exp(Y)$ . Then  $ab = \exp(X + Y) \in C^+$ . Thus  $C^+$  is a semigroup. Let  $a = \exp(X)$  be as above. Let  $v = \sum_{\alpha} v_{\alpha} \in V$  with  $v_{\alpha} \in \mathfrak{c}$ , then

$$\exp(X) \cdot v = \sum_{\alpha} e^{\alpha(X)} v_{\alpha}$$

and  $e^{\alpha(X)} > 1$  because  $\alpha(X) > 0$  for all  $\alpha$ .  $\square$

Choose a basis  $X_1, \dots, X_r$  of  $\mathfrak{a}$  such that the vectors  $X_1, \dots, X_k$  and the vectors  $X_{k+1}, \dots, X_r$  form a basis for the orthogonal complement of  $\mathfrak{c}$  in  $\mathfrak{a}$ . Here we use the inner product  $(X, Y) = \text{Tr}(XY^T)$ . As  $\mathfrak{c}^+$  is an open cone in  $\mathfrak{c}$  we can choose  $X_j \in \mathfrak{c}^+$ ,  $j = 1, \dots, k$ . Let

$$\Gamma_A := \left\{ \exp\left(\sum_{j=1}^r n_j X_j\right) \mid \forall j : n_j \in \mathbb{Z} \right\}.$$

Then  $\Gamma_A$  is a cocompact, discrete subgroup of  $A$  and every element of

$$\Gamma_A^+ := \left\{ \exp(n_1 X_1 + \dots + n_k X_k) \mid \forall j : n_j \geq 0 \right\} \setminus \{\text{id}\}$$

is expansive. As

$$\exp(n_1 X_1 + \dots + n_r X_r) \exp(m_1 X_1 + \dots + m_r X_r) = \exp((n_1 + m_1) X_1 + \dots + (n_r + m_r) X_r)$$

it follows that  $\Gamma_A^+$  is a subsemigroup of  $\Gamma_A$  such that  $\Gamma_A \Gamma_A^+ \subset \Gamma_A$ . Thus  $\Gamma_A$  is  $\gamma$  invariant for all  $\gamma \in \Gamma_A^+$ . We have therefore proved the following Lemma:

**Lemma 5.4.** *There exists a co-compact discrete subgroup  $\Gamma$  of  $A$  and a subsemigroup  $\Gamma_A^+$  such that each element of  $\Gamma_A^+$  is expansive and  $\Gamma_A \Gamma_A^+ \subset \Gamma_A$ .*

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